of gas is a mixture of these two, its refractivity will determine the proportions in which the components are present.

The observations were made by an apparatus similar in character to that already described, but designed to work with smaller quantities of gas. The space to be filled is only about 12 c.c., and if the gas be at atmospheric pressure its refractivity may be fixed to about 1/1000 part. By working at pressures below atmosphere very fair results could be arrived at with quantities of gas ordinarily reckoned at only 3 or 4 c.c.

The refractivity found for the Bath residue after desiccation was 0·896 referred to air, so that the proportional amount of helium is 8 per cent. Referred to the original volume, the proportion of helium is 1·2 parts per thousand.

"On the Changes produced in Magnetised Iron and Steels by cooling to the Temperature of Liquid Air." By JAMES DEWAR, LL.D., F.R.S., Fullerian Professor of Chemistry in the Royal Institution of Great Britain, and J. A. FLEMING, M.A., D.Sc., F.R.S., Professor of Electrical Engineering in University College, London. Received April 25,—Read May 21, 1896.

The action of the low temperature produced by liquid air upon the magnetic moment of steel magnets was studied by one of us in a few cases in a preliminary research made some time ago.* We have recently returned to the subject and made further investigations on the influence of the low temperatures thus obtained on magnetised iron and steels of very various compositions, with the object of determining the nature of the changes which take place in the magnetic moment of small magnets constructed of these metals, when cooled gradually or suddenly down to the lowest temperature obtainable by the use of boiling liquid air. The arrangements adopted in this investigation were as follows:—

A reflecting magnetometer consisting of three small magnetised needles of watch-spring steel, cemented to a concave glass mirror, suspended by a single cocoon fibre, was placed in a tube so as to be free from disturbance by draughts of air. The small magnets were 8 to 10 mm. in length. The image of a portion of the filament of an incandescent lamp was reflected by the mirror on to a divided scale placed at a distance of 70 cm. from the mirror. The edge of the very sharp image of the filament, focussed upon the scale,

* Friday evening discourse at the Royal Institution, "On the Scientific Uses of Liquid Air," by James Dewar, LL.D., F.R.S., January 19, 1894.

enabled any angular displacement of the magnetometer needle to be easily determined. The position of this magnetometer needle was regulated by the field produced by an external controlling magnet. The small magnet, the behaviour of which at low temperatures was to be studied, was placed behind the magnetometer, with its centre at a distance of 1 to 10 cm. from the centre of the magnetometer needle and its axis in a direction passing through the centre of the magnetometer needle, and at right angles to the direction of the undisturbed magnetometer needle. The magnet to be examined was fixed to a brass wire, held in a wooden support in such fashion that the magnet under examination could be easily removed from its position behind the magnetometer, and restored to it again exactly. A large number of samples of steel and iron were then prepared in the form of small needles, generally 15 mm. long and about 1 mm. in diameter. These steels comprised nickel steels, with various percentages of nickel; chromium steels, with various percentages of chromium; aluminium steels, with various percentages of aluminium; tungsten steels, manganese steels, silicon steel, ordinary carbon steels in various states of tempering, soft-annealed transformer iron, soft-iron wire, and the same irons hardened by hammering. For most of these samples of steels we were indebted to Mr. R. A. Hadfield, of Sheffield, who kindly furnished them to one of us in the form of wires.

These short steel magnets were then all magnetised to "saturation" by placing them for a few moments between the poles of a powerful electro-magnet. One by one they were then placed in position behind the magnetometer, and the deflection produced on the magnetometer needle observed. In any particular case this deflection may be taken as approximately representing the intensity of magnetisation of the sample, although, owing to the varying sizes of the sample and distance from the magnetometer, the deflections in the case of different magnets are not comparable with one another, and cannot be taken as indicating the relative intensities of magnetisation of two different samples. This, however, was not important, as our object was not to compare the absolute values of the magnetisation of different classes of steels, but to observe the mode of variation of the magnetisation of any one sample when cooled from ordinary temperatures down to the temperature of liquid air.

The method of proceeding was then as follows:—Having adjusted the image of the lamp filament to the zero of the scale, the small magnet under observation was placed behind the magnetometer, and the deflection of the magnetometer needle observed. A small vacuum-jacketed cup, filled with liquid air, was then brought up underneath the sample, and by its aid the magnet cooled suddenly *in situ* to a temperature in the neighbourhood of -186° C. In the

many cases this sudden cooling immediately deprived the magnet of a considerable percentage of its magnetisation, and the magnetic moment was reduced. This, however, was not universally the case. In some cases, as in that of the chromium steels, the first effect of this sudden cooling was an increase in the magnetic moment of the magnet; in other cases hardly any change in the magnetic moment at all. The vessel of liquid air was then removed, and the magnet allowed to heat up again, which it very quickly did, to the temperature of the room, or rather to a temperature at which the deposit of snow formed upon the needle immediately on coming out of the liquid air, fully melted. This was taken to be at about 5° C. It was found that each magnet had certain peculiarities of its own.

Taking first the ordinary carbon steel (a sample of knitting-needle steel) we observe the following facts :—

Knitting-needle Steel (a) *Tempered Glass Hard.*—The first effect of cooling this magnet was to diminish the magnetic moment by 6 per cent. On allowing the magnet to heat up again to the ordinary temperature, the magnetic moment still further diminished by about 16 per cent. On cooling again the magnetic moment increased 10 per cent., and from and after that time cooling the magnet always increased the magnetic moment, and allowing to heat up again to ordinary temperature always diminished the magnetic moment, the magnetic moment at −185° C. being about 10 per cent. greater than the magnetic moment at 5° C. The first effect, therefore, of the cooling was to permanently diminish the magnetic moment, but after a few alternations of heating and cooling, the magnet reached a permanent condition in which its moment, when cold, was greater than its moment when warm. These changes of magnetisation may be best represented as in the diagram in fig. 1, in which the firm lines represent to some arbitrary scale the moment of the magnet when at its ordinary temperature of 5° C., and the dotted lines represent to the same scale the moment of the magnet when cooled to −185° C.

Knitting-needle Steel (b) *Medium Temper.*—The same general results were obtained with knitting-needle steel tempered to a medium temper. The first effect of the cooling to the low temperature was to diminish the moment of the magnet. On allowing it to heat up again the moment of the magnet diminished still more. The next cooling caused an increase of magnetic moment, and from and after that time the steel settled down into a permanent condition in which the magnetic moment was greater at −185° C. than at 5° C. by nearly 20 per cent. of its value at 5° C. (see fig. 2).

Knitting-needle Steel (c) *Annealed Soft.*—The same general course of events was noticed in the case of the knitting-needle steel when made soft by heating to a red heat and allowing it to cool very

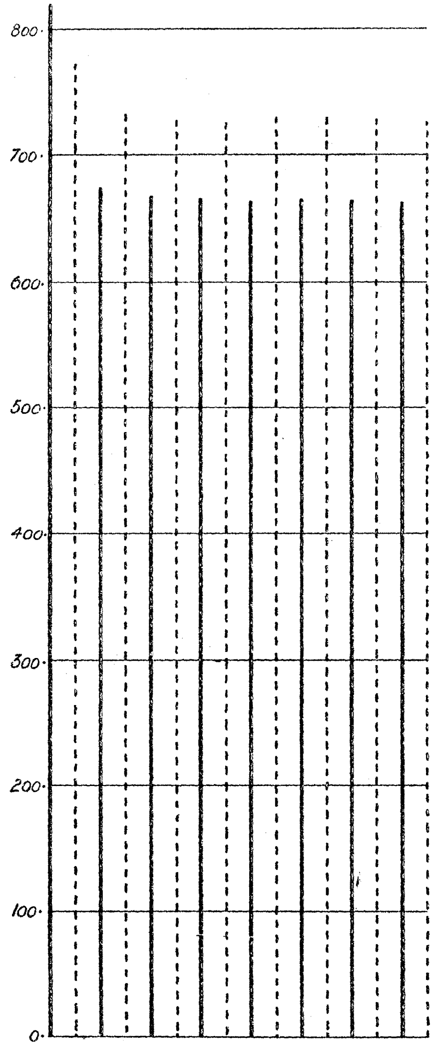

FIG. 1.—Knitting-needle steel (glass hard).

slowly. In this case, however, the first diminution of magnetic moment was still greater. On first immersion in the liquid air the magnet lost about 33 per cent. of its moment. On allowing it to heat up again to 5° C. it still further diminished in moment, and from and after that point it arrived soon at a permanent condition, in which its moment, when cold, was greater than its moment when warm by 30 per cent. of its moment at 5° C. These

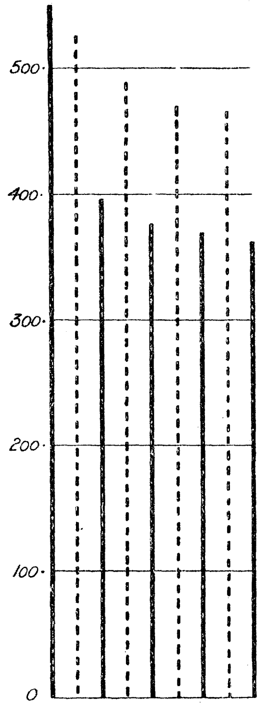

FIG. 2.—Knitting-needle steel (medium temper).

changes of the medium- and soft-tempered steel are represented by the lines in the diagrams 2 and 3, in which the firm lines are proportional to the magnetic moment of the magnet at 5° C., and the dotted lines proportional to the magnetic moment at −185° C. It will be seen that, in the case of this carbon steel, the effect of softening the steel is to make more pronounced the effect of the final temperature changes; the change of moment caused by cooling from the ordinary temperature to the temperature of liquid air, when the permanent condition has been reached, being in the case of the glass-hard steel an increase of magnetic moment of about 12 per cent.; in the case of the same steel with a medium temper about 22 per cent., and in the case of the same steel tempered very soft about 33 per cent. (see fig. 3).

Chromium Steels.—Observations were then made with the magnets of chromium steel, having respectively 0·29 per cent., 1·18 per cent., 5·44 per cent., and 9·18 per cent. of chromium. In all these cases the first effect of cooling the magnet was to cause at once an increase of magnetic moment, and the subsequent heating up again to the ordinary temperature caused a decrease of magnetic moment. These

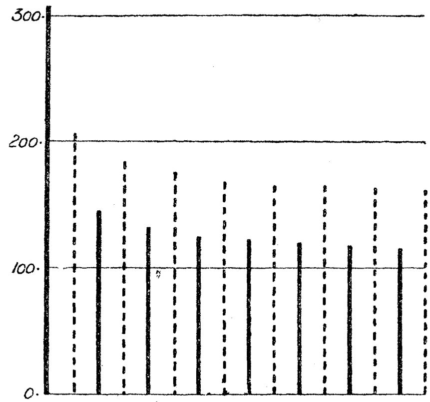

Fig. 3.—Knitting-needle steel (tempered soft).

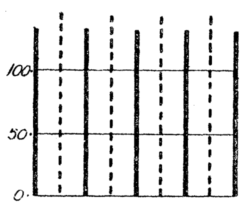

Fig. 4.—Chromium steel.

Cr	=	0·29
C	=	0·16
Si	=	0·07
Mn	=	0·18
Fe	=	99·30

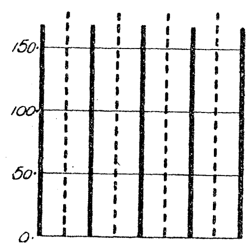

Fig. 5.—Chromium steel.

Cr	=	1·18
C	=	0·27
Si	=	0·12
Mn	=	0·21
Fe	=	98·22

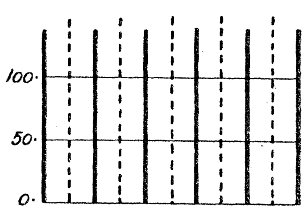

Fig. 6.—Chromium steel.

Cr	=	5·44
C	=	0·27
Si	=	0·50
Mn	=	0·61
Fe	=	92·68

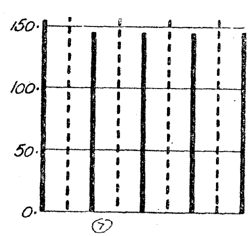

Fig. 7.—Chromium steel.

Cr	=	9·18
C	=	0·71
Si	=	0·36
Mn	=	0·25
Fe	=	89·50

magnets arrived almost immediately at their permanent condition, in which the magnetic moment, when cold, was greater than the magnetic moment when warm by about 12 per cent. The variation of magnetic moment in the case of these magnets is shown by the diagrams 4, 5, 6, and 7, in which the firm lines represent the magnetic moment when the magnet is at 5° C., and the dotted lines the magnetic moment at −185° C. It will be seen, therefore, that in the case of the magnets there was no such initial decrease of magnetisation as in the case of the carbon steel magnets. The analysis of these steels was furnished to us by Mr. Hadfield, and is appended to the diagrams. These steels are all in their hard condition, and possess considerable coercive force.

Aluminium Steels.—The aluminium steels employed had the following percentages of aluminium, viz.: 0·72, 1·16, and 1·60. In all these cases the first effect of cooling the magnet made of these steels was to cause a very small diminution in the magnetic moment, but not more than about 2 per cent. (see figs. 8, 9, and 10). The subsequent rise in temperature of the magnet again to its ordinary tem-

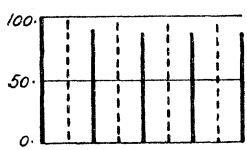

FIG. 8.—Aluminium steel.

Al	=	0·72
C	=	0·20
Si	=	0·12
Mn	=	0·11
Fe	=	98·85

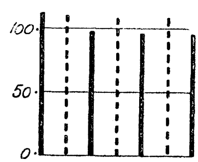

FIG. 9.—Aluminium steel.

Al	=	1·16
C	=	0·26
Si	=	0·15
Mn	=	0·11
Fe	=	98·32

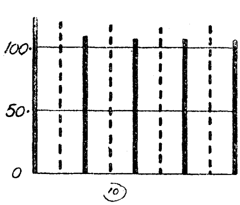

FIG. 10.—Aluminium steel.

Al	=	1·60
C	=	0·21
Si	=	0·18
Mn	=	0·18
Fe	=	97·83

perature, caused a still further fall in magnetic moment, and from and after that point the effect of cooling down to the temperature of

liquid air was to cause the magnet to possess a magnetic moment about 10 per cent. greater at $-185°$ C. than at $5°$ C. It will be seen, therefore, that these steels differ from the chromium steels in this respect, that whereas in the chromium steels the effect of the first cooling is to cause an increase in magnetic moment; in the case of the aluminium steels, the effect of the first cooling was to cause a decrease of magnetic moment, although much smaller relatively than in the case of the carbon steels.

Nickel Steels.—Experiments were then made with samples of nickel steel containing 0·94, 3·82, 7·65, 19·64, and 29 per cent. of nickel. These steels exhibited some rather interesting peculiarities. In the case of the nickel steel with 0·94 per cent. of nickel, the effect of the first cooling in liquid air was to cause a very small decrease in magnetic moment (see fig. 11), and the subsequent heating and cooling

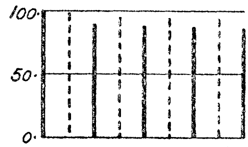

FIG. 11.—Nickel steel.

Ni	=	0·94
C	=	0·13
Si	=	0·23
Mn	=	0·72
Fe	=	97·98

brought the steel into a condition in which its magnetic moment, when cold, was always greater than its magnetic moment when warm, by about 10 or 11 per cent. In the case of the nickel steel with 3·82 per cent. of nickel, the effect of the changes of temperature was very similar (see fig. 12), and also in the case of the nickel steel having 7·65 per cent. of nickel the order of the changes was not very different—in this respect, that the magnetic moment when cold was

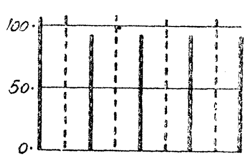

Fig. 12.—Nickel steel.

Ni	=	3·82
C	=	0·19
Si	=	0·20
Mn	=	0·65
Fe	=	95·14

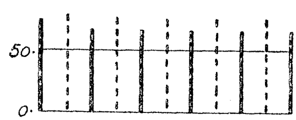

FIG. 13.—Nickel steel.

Ni	=	7·65
C	=	0·17
Si	=	0·28
Mn	=	0·68
Fe	=	91·22

greater than the magnetic moment when warm, when the permanent state had been reached. But it will be noticed from the diagrams (see fig. 13) that in the case of the 7·65 per cent. nickel steel, the effect of the first cooling was to cause a slight increase in magnetic moment. A remarkable peculiarity, however, was found in the case of the 19·64 per cent. nickel steel. In this case the effect of the first cooling was to cause a very considerable reduction of magnetic moment, very nearly 50 per cent., that is to say, the magnetic moment fell instantly, on cooling in the liquid air, to about half the value that it had at the beginning of the experiment. On taking the magnet out of the liquid air and allowing it to warm up again to the temperature of the room, the magnetic moment immediately *increased* again, and from and after that time the effect of the temperature change on the magnetic moment was such that the magnetic moment, when cooled to the temperature of liquid air, was always *less* than the magnetic moment at 5° C. by about 25 per cent. of the latter value. These relative changes are shown in the diagram (fig. 14). These experiments

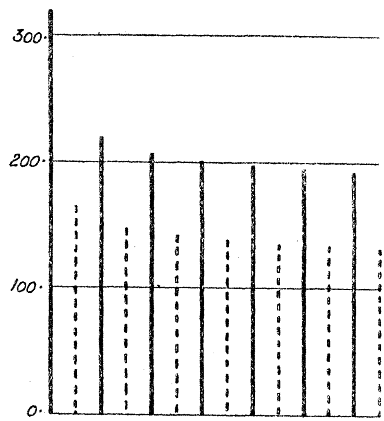

FIG. 14.—Nickel steel.

Ni	=	19·64
C	=	0·19
Si	=	0·27
Mn	=	0·93
Fe	=	78·97
		100·00

with the 19 per cent. nickel steel were repeated a great many times, and always with the same general results. The sample of 29 per cent. nickel steel was then examined, and it was found that the magnetic changes produced in it on heating and cooling were of the same general character as in the case of the 19 per cent. sample, only less

marked. Steels having these high percentages of nickel are, as Dr. J. Hopkinson has pointed out,* remarkable for the wide range of temperature within which they can exist in two states, one considerably magnetic, and one practically non-magnetic or but feebly magnetic. In these two states their mechanical and other physical properties are entirely different. In the experiments here mentioned, the nickel steel samples were in the magnetic condition. They are put into this condition by dipping for one moment in liquid air, and are only transformed back into the feebly magnetic condition by heating to a cherry-red heat. The 29 per cent. sample of nickel steel being in the magnetic condition was magnetised by contact with the poles of the electromagnet. On cooling it in liquid air it immediately lost about 20 per cent. of its moment, on warming up again to 5° C. it lost about 5 per cent. more, and from and after that point remained in a condition in which cooling the magnet to −185° C. caused its moment to become about 10 per cent. *less* than it was at 5° C. Hence the 29 per cent. nickel steel exhibits the same quality but in a less marked degree than the 19 per cent., in that its magnetic moment is decreased by cooling to −185° C., and recovers again on heating up to 5° C. In this respect the two samples of nickel steel differ from all other samples of steel which we have examined, in that they have a negative temperature coefficient for magnetic moment change with temperature, after the first change on cooling has taken place.

Pure Nickel.—In order to see if this peculiarity extended to pure nickel, we examined the behaviour of a small magnet made with Mr. Mond's pure nickel, but we found that such a nickel magnet, magnetised to saturation, behaved exactly as did a carbon steel magnet (see fig. 15). The effect of the first cooling to the temperature of liquid air was to diminish the magnetic moment. On allowing the magnet to heat up again to the ordinary temperature the moment diminished still more, and from and after that time the behaviour of the magnet was perfectly normal, that is to say, its magnetic moment when at 5° C. was less than its magnetic moment at −186° C., but only by about 3 or 4 per cent. of the latter value.

Silicon Steel.—A sample of silicon steel, containing 2·67 per cent. of silicon, behaved in a normal manner (see fig. 16). The magnet experienced a permanent diminution of moment on cooling for the first time, and after that, its magnetic moment when cold was greater than its magnetic moment when warm.

Soft Iron.—In order to determine if similar changes of magnetic moment could be produced in the case of soft annealed iron, small magnets of Swedish iron were prepared, formed of a short length, about 15 mm., of soft iron, or a small slip of annealed transformer iron. On magnetising these in a strong field, and testing them with

* 'Roy. Soc. Proc.,' 1890, vol. 47, p. 138.

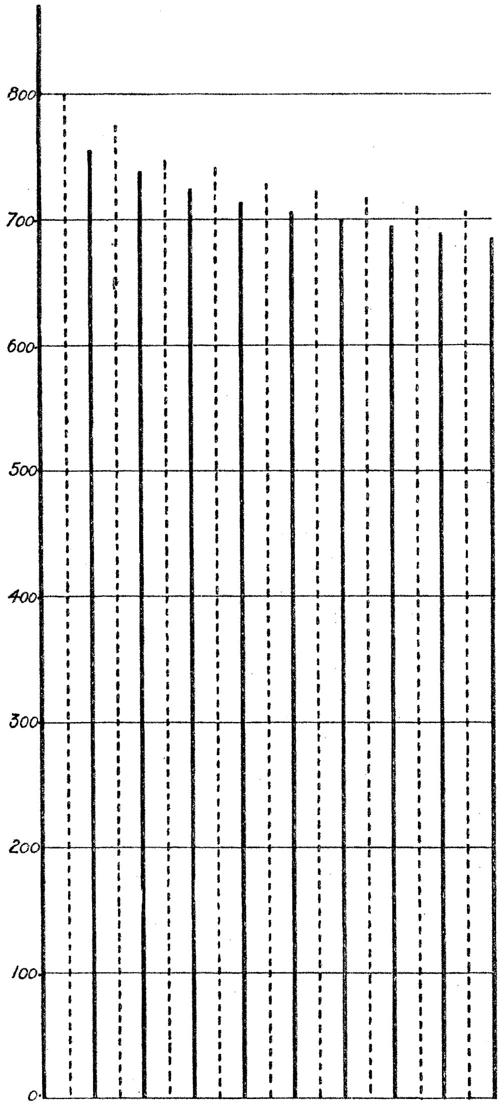

FIG. 15.—Mond's pure nickel.

the magnetometer, and cooling them by immersing in liquid air, it was found that the first effect of the cooling was to produce a small diminution in the magnetic moment, and the subsequent heating in some cases produced a further diminution of magnetic moment. In the first sample of soft iron, the wire was about 3 cm. long, and bent

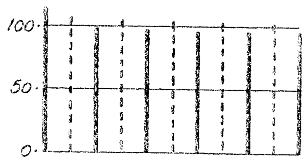

FIG. 16.—Silicon steel.

Si = 2·67
C = 0·20
Mn = 0·25
Fe = 96·88.

into a U shape, with ends about 10 mm. apart, and in this case the changes of magnetic moment, as shown in fig. 17, were similar to

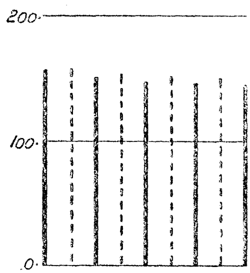

FIG. 17.—Soft iron.

those in the case of the carbon steels, only with very much narrower limits of variation. The first cooling hardly produced any change whatever in the magnetic moment of the magnet. On allowing it to heat up again, the magnetic moment was very slightly diminished, and thenceforth the changes of moment were such that the magnetic moment was greater when the magnet was cold than when it was warm, by about 2 or 3 per cent. of the latter value. In the case of a straight, soft iron magnet, formed of annealed transformer iron, the curious fact was noticed that whereas a rapid cooling of the magnet by plunging into liquid air hardly produced any effect on the magnetic moment after the first initial loss of magnetism had taken place on cooling, the effect of a slow cooling down to the temperature of $-185°$ C. was always to produce a permanent diminution of magnetic moment. Hence the magnetism of this soft iron sample could be frittered away by a process of slow cooling to $-185°$ C., and intermediate heating up to 5° C. These changes of moment are represented in the diagram of fig. 18.

Hard Iron.—A sample of the same iron, hardened by hammering, was tested, and was found to behave in a very similar manner to the

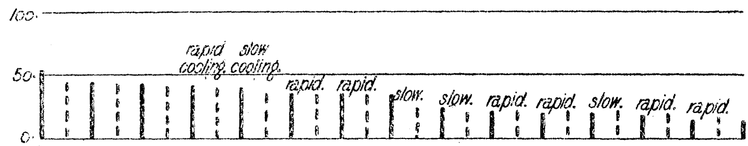

FIG. 18.—Annealed transformer iron.

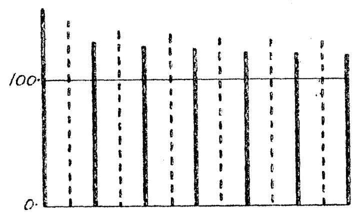

FIG. 19.—Hard transformer iron.

glass-hard carbon steel (see fig. 19), the changes in magnetic moment being relatively about the same percentage for the same temperature change: that is to say, the magnet had a moment of about 10 per cent. greater at $-185°$ C. than at $5°$ C.

A series of tungsten steels were then examined, having respectively 1, 7·5, and 15 per cent. of tungsten in them.

Magnets were prepared of these steels, both in the glass-hard condition and in a carefully annealed condition. These steels were found to resemble the simple carbon steels in that the first effect of cooling the magnet to $-186°$ C. was to cause a diminution of magnetic moment, and the subsequent warming up again to $5°$ C., a still further decrease in magnetic moment. From that time forth cooling the magnet always caused an increase of magnetic moment. The effect of increasing the percentage of tungsten was to cause a decrease in the variation of the magnetic moment over a given temperature range. That is to say, the hardened 15 per cent. tungsten steel temporarily lost magnetic moment to the extent of about 6 per cent. by heating up from $-185°$ C. to $5°$ C. when once the initial condition had been passed. The 7·5 per cent. tungsten steel lost moment to the extent of about 10 per cent., and the 1 per cent. tungsten steel lost moment to the extent of about 12 per cent. when the temperatures rose between the same limits. As regards these tungsten steels, softening the steel caused the magnetic moment to decrease by a greater percentage when heated up from $-185°$ C. to $5°$ C. than was found to be the case when the steel was in its hard condition. A sample of manganese steel containing 12 per cent. of manganese was rendered magnetic by heating for 24 hours to a dull red heat. A small magnet prepared from this steel was found capable of retaining

magnetism. On cooling it to -185° C., it slightly increased in magnetic moment, and on heating up again to 5° C., its magnetic moment decreased to the extent of about 3 per cent. of its moment at -185°C. There was no initial decrease of moment in this case. In this respect, therefore, it resembled the chromium steel magnets.

Broadly speaking, the results so far obtained are:—

(1) That the sudden cooling to the temperature of liquid air usually permanently decreases the magnetic moment of short magnets made of many varieties of steel, assuming them to have been initially magnetised in a strong field.

(2) This initial decrease is found both in hardened steels having great coercive force, and also in the same steels in a soft or annealed condition, and is especially conspicuous in the case of the 19 per cent. nickel steel.

(3) In the case of most steels so far examined, the effect of cooling magnets made of them to -185° C. is to temporarily increase the magnetic moment after the permanent magnetic condition has been reached.

(4) The exceptions to the above rule so far noted are the nickel steels with percentages of nickel from 19 to 29 per cent., in which case the magnetic moment is always decreased temporarily by cooling to -185° C., after the permanent magnetic condition has been reached.

(5) It appears from these experiments that one of the best ways of *ageing* a permanent magnet is to dip it several times into liquid air. It then arrives at a constant condition in which subsequent temperature changes have a definite effect, and in which the subpermanent magnetism is removed.

Note added May 4.

Since the 19 per cent. nickel steel magnet increases in magnetic moment when heated from -185° C. to $+5^\circ$ C., and since it is well known that at some higher temperature it would lose magnetic moment altogether, it was considered very desirable to ascertain the temperature at which it would have its maximum magnetic moment. The magnet was accordingly heated (on April 2) in an oil bath gradually up to a temperature of about 300° C., and the deflections of the magnetometer observed at intervals, both as the temperature rose and as it fell. The result showed that this nickel steel magnet continued to increase in magnetic moment, until a temperature of about 30° C. was reached, and the magnetic moment then began to decrease.

At a temperature of $+300^\circ$ C., the moment of the magnet was not much greater than it was at -185° C. On cooling down again from

300° C., the moment increased, but not to the same maximum as before, and on repeating the cycle of temperature from about 15° C. to 300° C., the magnetic moment gradually varied, in the manner shown in fig. 20, and the temperature of maximum magnetic moment

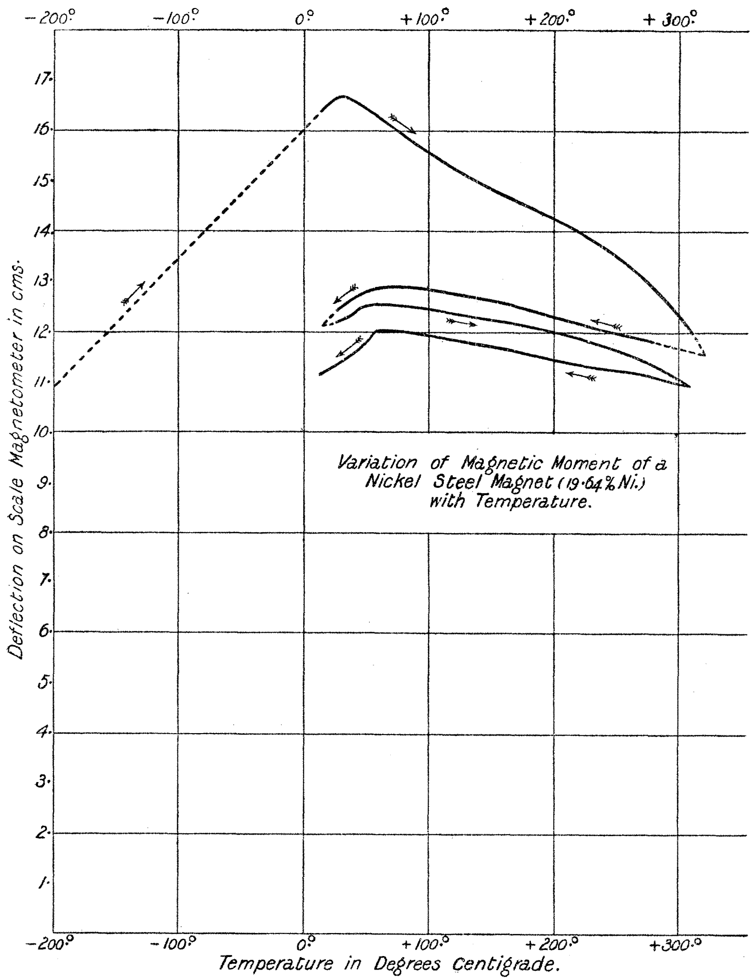

Fig. 20.

gradually shifted upwards to about 56° C. This magnet is, therefore, an interesting case of a sample of steel which, when magnetised, has a maximum magnetic moment at a certain temperature.